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An ultra high sensitive current sensor based on Superconducting Quantum Interference Device

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Abstract

The design of the reported current sensor is based on a suitable superconducting intermediary (matching) magnetic flux transformer magnetically coupled to a niobium based dc-SQUID (Superconducting Quantum Interference Device). The 60 square niobium turns (20 μm width) signal coil is tightly coupled to the matching flux transformer consisting of a square single turn primary coil connected in series with a multiturn secondary coil. The obtained signal current to magnetic flux transfer factor (current sensitivity) is equal to 62 nA/Φ_0 measured by using a current sensing noise thermometer technique. The sensor has been characterized in liquid helium by using a direct coupling low noise readout electronic and the flux locked loop configuration. Despite the circuit complexity, the sensor has exhibited a smooth and free resonance voltage-flux characteristic ensuring a stable working operation. Considering a SQUID magnetic flux noise $\sqrt{S_\Phi}$ =1.8 μΦ_0/√Hz at T=4.2 K, a current noise as low as 110 fA/√Hz has been obtained. Due to his high performance such sensor can be employed in all application requiring an extremely current sensitivity, like the readout of the gravitational wave detectors and the current sensing noise thermometry.

Keywords: Current sensor; SQUID

1. Introduction

The high sensitive current sensors are successfully employed in many applications including the sensing noise thermometry [1] and the readout of gravitational wave detectors[2] or transition edge

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sensors [3]. In particular, ultra high sensitive sensor are based on Superconducting Quantum Interference Devices (SQUIDs) which have an equivalent energy sensitivity that approaches the quantum limit [4].

To achieve a current noise spectral densities of a few fA/Hz$^{1/2}$, different approaches have been employed such those based on a ferromagnetic core [5] or a high Q resonant circuit tuned to the axial resonant frequency of a single trapped ion in a Penning trap [6]. Nevertheless, these approaches are impractical and often introduce extra noise contributions. A suitable way to obtain a practical and reliable SQUID current noise is obtained by using a flux transformer which converts easily the electrical current into a magnetic flux treading the SQUID loop and allows to obtain fully integrated sensors. Recently, superconducting current sensors based on the SQUID with a parallel washer configuration including an integrated signal coil (single transformer) [7], SQUID array [8], SQUID in a two stage configuration [9], exhibiting a spectral current noise of few hundreds of fA/Hz$^{1/2}$ at T=4.2 K has been reported. A high coupling between the signal coil and the SQUID could be obtained by using a design based on a double transformer [10,11] including a matching (intermediary) transformer inserted between the signal coil and the input terminals of the conventional configuration. With respect to single transformer it allows to efficiently couple the low-inductance SQUID with a very high signal coil inductance (tenths of μH), obtaining an ultra low electric current noise

Here, an ultra high sensitive SQUID current sensor based on a multiturn signal coil coupled to a suitable SQUID magnetometer is reported.

2. Sensor design

The fully integrated device has an area of 1 cm^2 and it includes a signal coil, an intermediary flux transformer, a SQUID in a washer configuration, a feedback coil for Flux Locked Loop (FLL) operation and a thin film resistor network useful for the current noise characterization of the sensor. The signal coil, consisting of a superconducting 60-turns coil, is magnetically coupled to the intermediary transformer (Fig. 1). The primary coil of the intermediary transformer consists of a single superconducting square coil having a side length of *10 mm* and a large side width (*2.5 mm*) in order to accommodate the signal coil's turns.

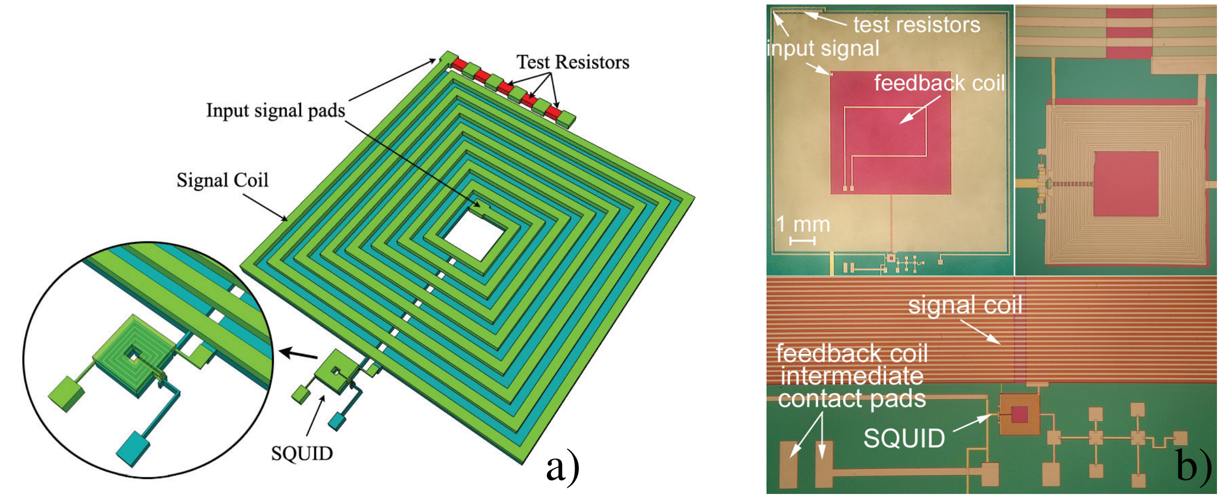

Fig. 1 a) Sketch of the whole device and a particular of the SQUID in a washer configuration inductively coupled with the underlying input coil. b) Fully integrated device picture showing the primary and signal coils, the test resistors and the SQUID.

The primary coil (L_p= 9.3 nH) is connected in series with a 12-turn input coil (L_i=33 nH), which is coupled to the SQUID loop in a washer configuration having a large inductance L=250 pH, in order to increase the flux gain [12]; the consequent performance degradation, due to a non-optimal β_L value (>1) is avoided by inserting a damping resistor across the SQUID inductance [13]. A resistive feedback coil is located in the primary coil's hole (Fig. 1b) and acts also as device heater in the case of entrapped flux. An important figure of merit for a SQUID current sensor is the input current to magnetic flux transfer factor I_Φ=1/M (current sensitivity), that is the input current value flowing in the signal coil to couple a flux quantum (Φ_0=2.07×10-15 Wb) in the SQUID loop. The spectral density of the current noise is related to the SQUID magnetic flux noise by a simple expression: $\sqrt{S_I}= I_\Phi \cdot \sqrt{S_\Phi}$. The current sensitivity can be easily calculated by evaluating the current in the signal coil required to couple a flux quantum in the SQUID:

$$i_s = \frac{(L_p + L_i)\Phi_0}{M_i M_s} = \frac{(L_p + L_i)\Phi_0}{k_i\sqrt{LL_i}\,k_s\sqrt{L_s L_p}} \Rightarrow I_\Phi = \frac{i_s}{\Phi_0} \cong \frac{(L_p + L_i)}{(k_i \cdot k_s \cdot n_i \cdot n_s \cdot L \cdot L_p)} \qquad (1)$$

Where M_i and M_s are the mutual inductances between the input coil and the SQUID and between the signal coil and the primary one respectively, L_s is the signal coil inductance, k_i and k_s are the corresponding coupling constants and n_i and n_s are the turn numbers of the input coil and the signal coil respectively. By using the numerical values reported above for the inductances and a value of 0.95 for both coupling constants, we can estimate a current responsivity value as low as 60 nA/Φ_0 corresponding to a mutual inductance M=34.5 nH. The fabrication process, based on the niobium technology, is well described in ref. 14. A picture of the fully integrated SQUID current sensor is shown in fig. 1b.

3. Experimental performance and discussion.

The SQUID sensor has been characterized in liquid helium at T=4.2 K in a coaxial double shield (lead and cryoperm) using a direct coupling low noise read-out electronic. The voltage to magnetic flux characteristic (V-Φ), the current sensitivity (I_Φ) and the magnetic flux noise spectral density ($\sqrt{S_\Phi}$) has been measured. The critical current of the SQUID sensor was $2Ic=24\ \mu A$ the shunt resistor and junctions capacitance were respectively $R_s=3.6\ \Omega$ and $C=1.7\ pF$ corresponding to a $\beta_C=2\pi I_c C R_s^2/\Phi_0$ value of 0.8. The V-Φ characteristic (inset of figure 2a) shows a large voltage swing (ΔV=60 μV) with a maximum responsivity measured on the steeper side of the characteristic equal to V_Φ=310 μV/Φ_0.

In figure 2a, the magnetic flux noise spectral density, measured at T=4.2 K in FLL configuration, with the input signal open, is reported. The noise level measured in the white region is 2.9 μΦ_0/√Hz, while the intrinsic one, obtained by subtracting the amplifier contribution, is equal to 1.8 μΦ_0/√Hz.

The measurement of the current sensitivity I_Φ is based on a current sensing noise thermometer technique. By closing the signal coil on the integrated test resistors, the current generated by a Nyquist noise in the test resistor induces a magnetic flux noise in the SQUID:

$$\sqrt{S_\Phi} = \frac{1}{I_\Phi}\sqrt{\frac{4k_B T}{R_t}} \Rightarrow I_\Phi = \sqrt{\frac{4k_B T}{S_\Phi R_t}} \qquad (2)$$

Where R_t is the test resistance value and k_B is the Boltzman constant. The figure 2b shows the magnetic flux spectral density values as a function of $R_t^{-1/2}$ measured when the signal coil is closed on the different test resistors (50 Ω, 8 Ω, 5.6 Ω and 4 Ω). As expected from equation (2), it is evident the linear behavior of the noise as a function of $R_t^{-1/2}$; from the slope of linear best fit a current sensitivity of I_Φ=62 nA/Φ_0 is obtained, in excellent agreement with the prediction of equation (1). Considering the SQUID intrinsic flux noise value (1.8 μΦ_0/√Hz), a current noise spectral density of $\sqrt{S_I}$=110 fA/√Hz is obtained which is about three time smaller than the noise of other SQUID of the same category [7-9].

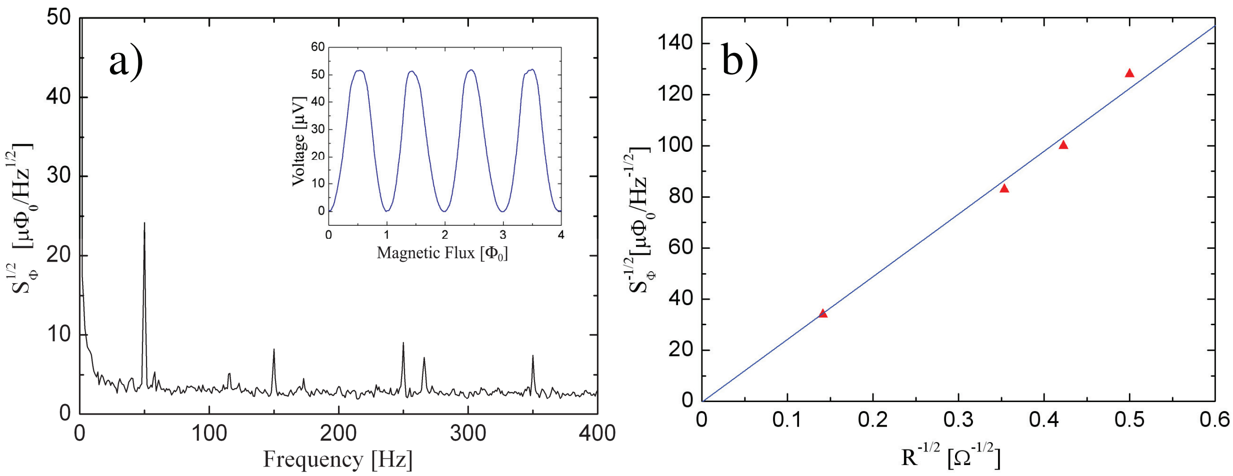

Fig. 2 *a)* Magnetic flux spectral density of the sensor in flux locked loop configuration, using a direct coupling scheme with a low noise readout electronics when the signal coil is open. In the inset the voltage to flux characteristic (V-Φ) of a SQUID current sensor is reported. *b)* Magnetic flux spectral density values, measured in the white region, as a function of the inverse of square root of the resistor value (R_t) connected to the signal coil. The slope of the linear best fit curve (straight line) provides a current sensitivity (I_Φ) of 62 nA/Φ_0. All the measurements was performed at T=4.2 K

4. Conclusions

The sensor design, based on an suitable double transformer, has been finalized to get both a very low current to magnetic flux transfer factor and a suitable voltage to flux characteristic. The effectiveness of the device, confirmed by the experimental results, makes it suitable in all applications based on the measurement at low frequency of ultra small electric currents.

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